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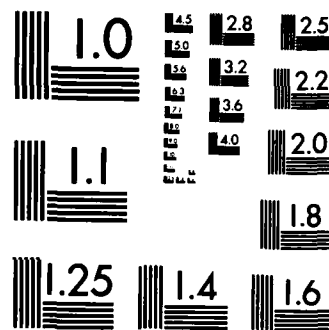
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# ENGINEERING ASSESSMENT OF TEG AND TEG/FC TECHNOLOGY GROWTH POTENTIAL

## FINAL REPORT

### PHASE II

## THERMOELECTRIC GENERATOR AND FUEL CELL TECHNOLOGY GROWTH POTENTIAL

*to*

SYSTEMS ANALYSIS DIVISION  
PROGRAMS AND ANALYSIS DIRECTORATE  
U.S. ARMY MOBILITY EQUIPMENT RESEARCH  
AND DEVELOPMENT COMMAND  
FORT BELVOIR, VIRGINIA 22060

CONTRACT NO. DAAK70-79-D-C036 TO 0020

*by*

ARTHUR D. LITTLE, INC.  
CAMBRIDGE, MA 02140

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OCTOBER 1981

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AND  
TEG/FC TECHNOLOGY GROWTH POTENTIAL

FINAL REPORT

PHASE II

THERMOELECTRIC GENERATOR AND FUEL CELL  
TECHNOLOGY GROWTH POTENTIAL

Contract No. DAAK70-79-D-0036 TO 0020

to

U.S. Army Mobility Equipment  
Research and Development Command  
Fort Belvoir, Virginia 22060

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Arthur D. Little, Inc.  
Cambridge, MA 02140

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## **FOREWORD**

This work was performed under the sponsorship of the U.S. Army Mobility Equipment Research and Development Command (MERADCOM). The work was performed by Arthur D. Little, Inc. of Cambridge, MA 02140, under T.O. 0020 of contract number DAAK70-79-D-0036. Mr. Roger G. Long, Mr. W. David Lee and Dr. John Parry were the principal investigators. This report was prepared under the guidance of Mr. Leon Medler of MERADCOM as the Technical Point of Contact and Mr. K.J. Dean of MERADCOM as the Contract Officer's Representative.

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## 1.0 INTRODUCTION

### 1.1 PURPOSE

The United States Army desires a Silent Lightweight Electric Energy Plant (SLEEP) for tactical operations. The thermoelectric generator (TEG) and fuel cell technologies appear to be acceptable candidates to meet this objective. This report presents a comparative analysis of the future potential of TEGs and fuel cells to meet specific criteria. The focus of this study is on small electric generators in the range of 0.5- to 10-kW electrical output.

### 1.2 DESCRIPTION OF TECHNOLOGIES

The TEGs referred to in this report consist of an array of thermocouple elements heated on one face by a self-contained burner and cooled on the other face by air or a liquid-to-air system. The thermocouple elements are typically semiconductor material, and they develop a voltage proportional to the temperature differential maintained across them and an available current that is proportional to the heat flow.

Fuel cells consist of a two-stage system in which fuel is first processed into hydrogen and then fed, together with air, to a cell stack. In the cell stack, hydrogen releases electrons in reaction with the oxygen (from the air) thus creating water and a flow of electrons. The cell stack collects the electrons liberated in the reaction and delivers the electrical energy to the external circuit or load. ←

### 1.3 SCOPE OF WORK

A comprehensive analysis of current TEG technology is covered in the Phase I report "Engineering Assessment of TEG," dated September 1981.

In Phase II a comparative analysis of the growth potential (10- to 20-year projection) in TEG and fuel cell technologies was completed with respect to specific critical issues related to field deployment.

### 1.4 APPROACH

Evolving TEG and fuel cell technologies were identified in terms of a 10-year and a 20-year projection of growth from existing technologies. The starting points of the projections were the current TEG technology, as described in the Phase I report, and fuel cell technology described in Chapter 2 of this report.

Specific developments and their impact on major subsystem elements were identified. A representative technology was selected where multiple developments with essentially similar impacts (e.g., new thermoelectric materials) are envisioned.

The comparative evaluation was based on the critical issues identified in the task order and are listed in Table 1.

**TABLE 1**

**CRITICAL ISSUES FOR COMPARATIVE PROJECTION**

1. Technical performance and efficiency
2. Operational characteristics (start up and shut down)
3. Size and weight
4. Logistic support required
5. RAM (Reliability, Availability and Maintainability)
6. Acoustic noise and infrared (IR) emission
7. Cost
8. Product/technology base
9. Technical and cost risk

## 2.0 CURRENT FUEL CELL TECHNOLOGY

### 2.1 FUNDAMENTAL PRINCIPLES

#### 2.1.1 Introduction

A fuel cell is an electrochemical reactor in which the chemical energy of a fuel is converted directly into electricity. Since each individual cell produces a low-voltage ( $\sim 0.6$  volts) direct current, several must be arranged in a series to provide practical voltage levels. Each cell produces about 100 amps of current per square foot of area. At present, fuel cells operate on methanol or a low-distillate fuel, such as naphtha or JP-4, which is used to produce hydrogen for the fuel cell stack.

When a fuel cell is in operation, hydrogen is oxidized spontaneously at one catalytic electrode releasing an electron to the outside circuit in the cell, and oxygen from the air is reduced at another (the cathode) consuming the electron. Water is produced in the electrolyte between the two electrodes. Successful operation of a fuel cell depends on the chemical reactions occurring rapidly, on maintaining a nearly constant operating temperature and on controlling the water content of the cell. The water produced is carried out of the cell in vapor form by excess air supplied to the cathode.

The most attractive feature of current fuel cells is the high operating full load efficiency ( $\sim 40\%$  in units larger than 40 kW, somewhat less in smaller units in the 1-kW range) and good part load efficiency. The different fuel cell types are usually classified by the type of electrolyte; the differences will not be discussed here, except to state that present technology is almost exclusively phosphoric acid.

#### 2.1.2 Voltage

The open circuit voltage of a fuel cell is defined by thermodynamic laws and is approximately 1.2 volts. When current is drawn, this voltage drops as a result of a combination of the following:

- The internal resistance of the cell (ohmic),
- A non-linear resistance related to the chemical reactions at the electrodes, and
- Diffusional resistances.

In current practice, a terminal voltage of close to 0.6 volts under load is used on the basis of optimization of the size and weight of the total system. Some improvement in this figure can be expected with improved catalysts to speed up the chemical reactions.

### 2.1.3 Current

The available current is not an independent variable, but is directly proportional to the electrode area.

### 2.1.4 Power Output and Efficiency

A fuel cell stack operating on pure hydrogen can operate at close to 60% thermal efficiency. On the partly diluted hydrogen (carbon dioxide and steam diluents) from a fuel processor, this drops to about 40%. Unburned hydrogen in the exhaust can be used as a source of heat in the fuel processor to recover some of the lost efficiency. In a complete power plant producing a.c., other sources of inefficiency include parasitic loads and the losses in the power conditioner. The partitioning of the energy losses of a typical 1.5-kW methanol fuel cell is shown in Figure 1.

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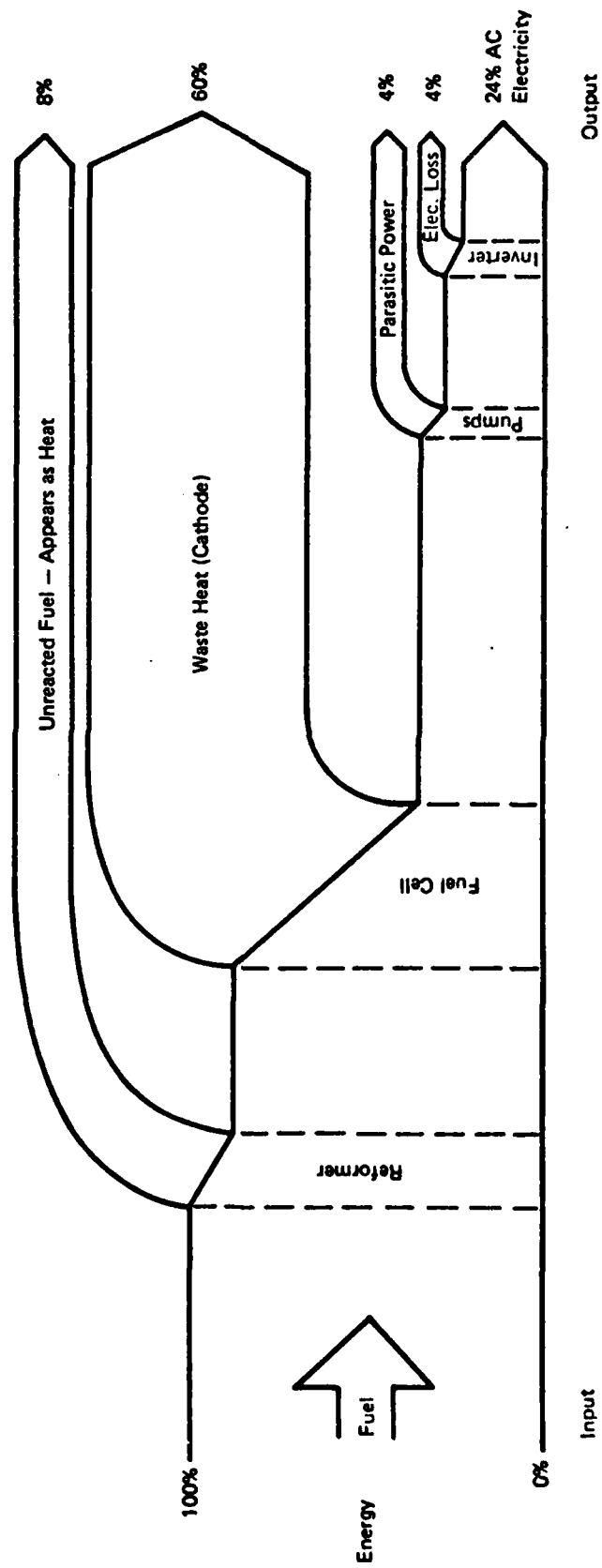


FIGURE 1 ENERGY PARTITION OF A 1.5-kW METHANOL FUEL CELL



### 2.1.5 Fuel Processor

A fuel cell stack operates on hydrogen or a mixture of hydrogen and carbon dioxide and, therefore, conventional logistic fuels must be "processed" or converted to these fuel forms for use with fuel cells. Fuel processing of conventional fuels involves a primary fuel conversion step in which the chemical structure of the molecules in the primary fuel are "reformed" into hydrogen and carbon oxides or other by-products. This can be accomplished by mixing vaporized fuel with steam and heating the mixture to promote the reactions. To offset the slower reaction rate at low ambient temperatures, a catalyst is often used.

Several types of reforming processes have been developed and are now being adapted for fuel cell systems. These are classified as follows:

- Conventional Steam Reforming (CSR),
- Low Temperature Reforming (LTR), and
- Adiabatic Reforming (ATR).

All three are catalytic processes. The most important difference among the processes is the range of primary fuels which each can accept. The fuel flexibility aspect is summarized below:

<u>Technology</u>	<u>Demonstrated Fuel Capability</u>
CSR	Natural Gas, LPG, Gasoline, Naphtha, Alcohols
LTR	Methanol
ATR	Natural Gas, LPG

In addition to its primary fuel conversion function, the fuel processor may include hydro-desulfurization and carbon monoxide shift conversion. The inclusion of these steps depends on the chemical purity and molecular structure of the primary fuel.

## 2.2 CURRENT DESIGN PRACTICE

The present design of phosphoric acid fuel cells has evolved over some 15 years. The electrodes are a porous composite of a conductive catalyst (precious metal supported on carbon) and a hydrophobic (non-wetting) binder. The phosphoric acid electrolyte is sandwiched between two electrodes contained by capillarity in a finely divided silicon carbide powder. The fuel cells in a stack are separated by

graphite sheets that have a special thermal retreatment for corrosion resistance. There are several effective designs for electrode and graphite plate construction to provide gas distribution and efficient current collection. Some examples are shown in Figure 2. Note that each involves cross flow of the fuel gas and air which allows relatively straightforward manifolding of the stack. End plates and tie rods complete the physical structure.

The present design allows for some diversity in stack cooling. The stack has to reject slightly more heat energy than the electrical energy generated. Two basic options exist, liquid cooling and air cooling. In liquid cooling, flat plates containing recirculating coolant are built into the cell stack at intervals of approximately every five cells. The manifolding adds complexity to the system, but cell temperature can be carefully controlled and maintained at a uniform level through the stack.

In the air cooling process sufficient air is blown through the stack to control the temperature. This is well in excess of the air required for the electromechanical reaction. The cathode air stream is also responsible for water removal, and at high velocities there can be problems of water depletion and entrainment of phosphoric acid. Cooling air can be routed through the cell separately from the process air for the cathode, and the process air and cooling air can be separated by a manifold thus eliminating entrained acid in the cooling loop. Designs for efficient distribution of air over the cathode surface have made a 25-mV improvement of the cell voltage at the same current drain.

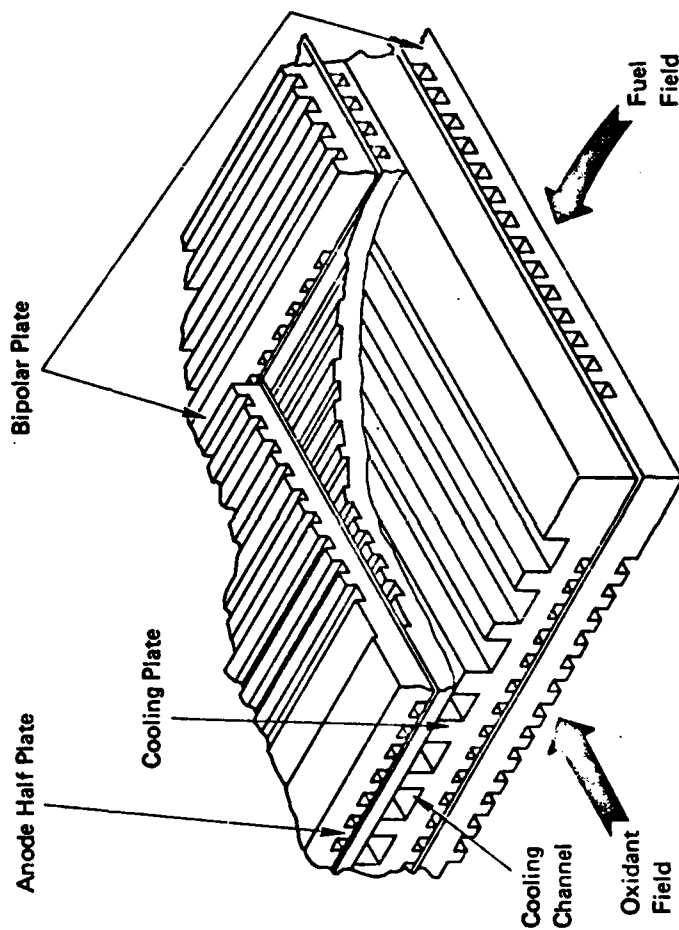
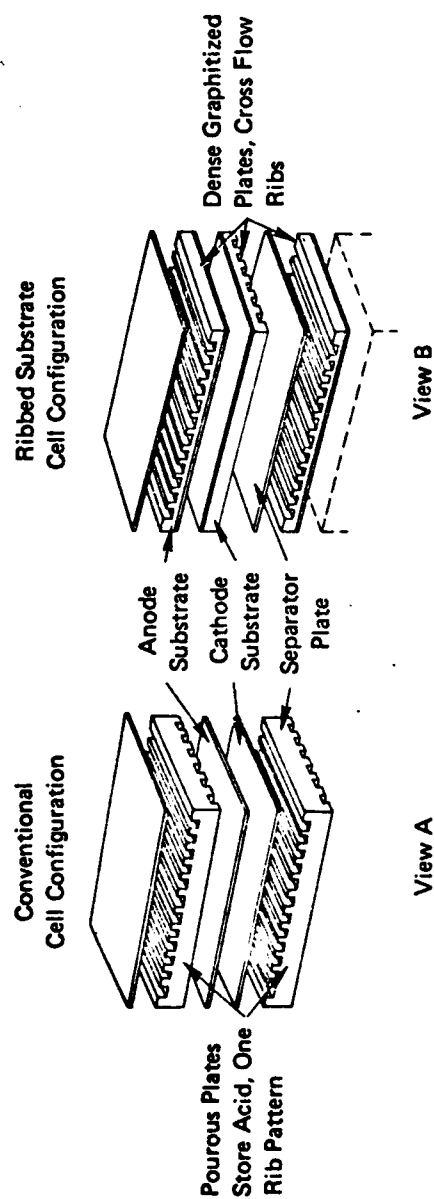


FIGURE 2 CUTAWAY VIEW OF DISTRIBUTED GAS (DIGAS) STACK

### 2.2.1 Fuel Processor

At present, fuel processing in the phosphoric acid fuel cell is done by conventional steam reforming (CSR) technology. This technology has been used commercially for 40 years for reforming natural gas to synthesis gas for the production of methanol and ammonia. It operates at temperatures in the range of 770-830°C and produces hydrogen with 1% (molar) concentration of carbon monoxide. [1]\* This fuel processor is fully operational with light hydrocarbon fuels and alcohols.

For several years, the U.S. Army at Ft. Belvoir has been developing a low-temperature reforming process which is specifically designed around methanol as a fuel. This process uses a somewhat different catalyst and operates at temperatures in the range of 200-315°C. The fuel processor operates only on mixtures of methanol and water.

### 2.2.2 Fuel Cell Generator

The Army has established a fuel cell program for a 1.5-kW, 3-kW and 5-kW design using methanol as the fuel. United Technologies Corporation (UTC) is under contract to provide four 1.5-kW units by the Fall of 1981, and Energy Research Corporation (ERC) will develop the 3-kW and 5-kW units. A process schematic of the UTC power unit excluding power conditioner is shown in Figure 3. Premixed methanol/water fuel from an external supply is pumped through a filter to a reservoir with a high-level shut-off valve. The fuel is pumped from the reservoir to the fuel processor by a magnetically driven gear pump. The pump meters the fuel flow and is used to modulate the fuel rate.

The fuel enters the fuel processor where it is vaporized and passed over a catalyst in a tube heated by a burner. The reformer burner is fired with anode vent gas which contains some unused hydrogen. The methanol/steam mixture is converted to hydrogen and carbon dioxide in the catalyst bed.

Processed fuel is sent to the cell stack where it combines with oxygen from the cathode air and produces an electric potential which causes current to flow in an external circuit. The spent fuel exits the anode and is returned to the fuel processor as fuel for the reformer burner.

Cathode air and cooling air are supplied by an axial fan. The same fan also supplies air to the reformer and startup burners. The cell stack recycle air line in conjunction with the inlet and outlet dampers controls the ratio of fresh air to recycle air. This action controls the temperature of the air entering the stack.

\*Numbers in brackets are references listed on page 56.

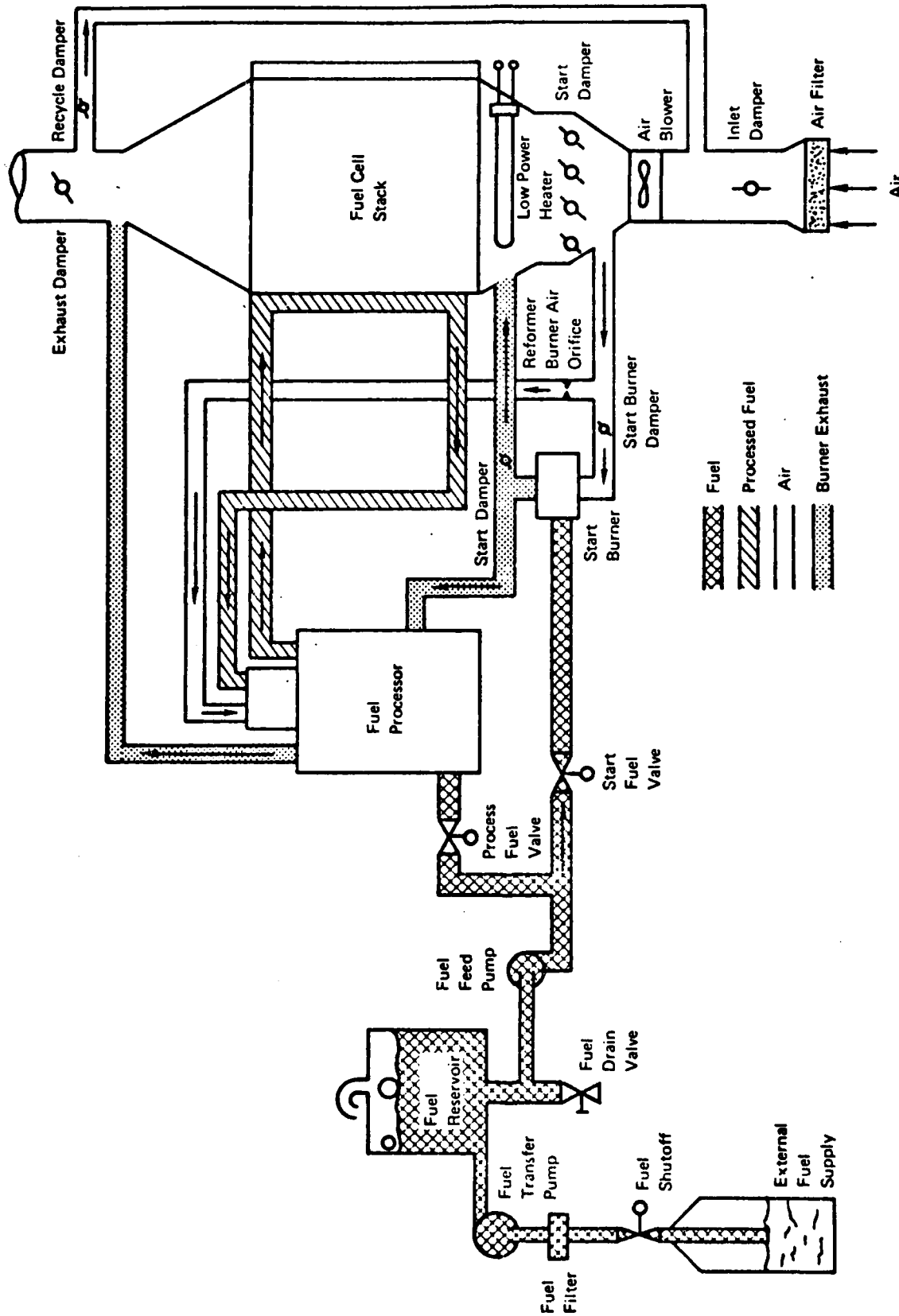


FIGURE 3 SCHEMATIC OF 1.5-KW POWER UNIT

Source: United Technology Corporation.

A startup burner is provided to heat up the reformer and cell stack to operating conditions before the main fuel valve is opened. The startup burner is fired with the same premixed fuel as used for feed to the reformer.

## 2.3 TECHNICAL PERFORMANCE AND EFFICIENCY

Typical performance to be expected from a single fuel cell is a current density of 100-200 Amperes per square foot at 0.6 volts. The efficiency of a fuel cell is not limited by the Carnot cycle, since it is isothermal in operation. Its energy output is determined by the free energy (G) of the chemical reactions taking place at the electrodes. Since the free energy is not equal to the thermal energy of the reaction (H), the intrinsic thermal efficiency of a fuel cell is:

$$\eta = \frac{\Delta G}{\Delta H}$$

and is typically in the 80-90% range. However, when current is drawn from the cell in operation, other sources of inefficiency come into effect. These include the internal resistance of the cell, resistances related to the chemical reactions and diffusional processes and to incomplete utilization of the fuel. With the effects minimized to the fullest extent, cell stack efficiencies of 55-60% can be achieved; if the inefficiencies of the fuel processor and system integration are taken into account, the overall efficiency falls to about 30-40%. Conservative design and smaller units typically achieve efficiencies in the 25-30% range.

### 2.3.1 Environmental Performance

A drop in the operating temperature of a fuel cell may have a pronounced effect on the governing chemical reaction rate, thus reducing the output. However, the primary cell reaction is exothermic and releases sufficient heat to maintain a nearly constant stack temperature over a wide range of ambient temperature. Close control of stack temperature is accomplished by adjusting cooling air used to remove internally generated heat not used in the cell reaction. Thus, the fuel cell efficiency is relatively insensitive to changes in ambient temperature during steady operation.

Elevation or decline in ambient pressure will reduce the air mass flow delivered by a constant speed fan. However, the cooling system normally has sufficient capacity to maintain the cell stack temperature at the design point up to 8000 feet at 35°C ambient. A slight fall in performance at 8000 feet can be attributed to lower oxygen pressure.

### 2.3.2 Part Load Operation

The part load efficiency of a fuel cell is nearly constant down to 40% of rated power. Table 2 summarizes the part load performance of the 1.5-kW UTC fuel cell, based on the average of the initial and end-of-life consumption. [2].

**TABLE 2**  
**PART LOAD EFFICIENCY**

<u>% Load</u>	<u>% Efficiency</u>
20	14
40	18
60	22
80	22
100	22

### 2.4 STARTUP PERFORMANCE

The fuel processor must be raised to an operating temperature of approximately 290°C (1550 Btu/per rated kW) and the cell stack to 177°C (2250 Btu/per rated kW). This is accomplished by firing the startup burner and directing hot exhaust gas through the stack-cooling passages and reformer. Startup is monitored by a self-contained control system. Electric power is required during startup to operate the blower, burner, and control system. The startup electric power is provided by an on-board battery. The startup time is governed by the size of the startup burner and the heat capacity of the cell stack and reformer. Table 3 summarizes the estimated startup burner requirements. In the present 1.5-kW generator design, the startup burner is rated at 100,000 Btu per hour, capable of starting the unit in 5 to 10 minutes.

**TABLE 3**  
**STARTUP REQUIREMENTS OF A FUEL CELL**

<u>Unit Size (kW)</u>	<u>Heat Input to Start from -32°C (Btu)</u>	<u>Burner Size Required to Start in 10 Minutes<sup>a</sup> (Btu/hr)</u>
0.5	2,185	16,500
1.5	5,675	42,600
3	10,490	78,700
5	16,590	124,400
10	31,180	233,850

<sup>a</sup> Assume 80% heat recovery from combustion gases.

## 2.5 SIZE AND WEIGHT

The performance figures cited above correspond to cell stacks that produce from 5 to 10 kW/ft<sup>3</sup> in large sizes of 5 kW or more. In smaller sizes, the energy density is somewhat lower. On a weight basis the energy density of the cell stack is ~10 lbs/kW plus the weight of end plates which are usually of substantial thickness and weight. Depending on detailed design, a complete power plant, including fuel processor, power conditioner, startup battery, etc., can be from five to ten times greater in volume and weight than the fuel cell stack alone.

The UTC 1.5-kW methanol fuel cell is 8.3 ft<sup>3</sup> and a total weight of 250 lbs (cell 45 lbs, conditioner 40 lbs, processor 20 lbs, batteries 45 lbs, plumbing and ducting 45 lbs, structure 36 lbs, controls/monitors 12 lbs, startup burner 8 lbs).

## 2.6 LOGISTIC SUPPORT REQUIRED

Methanol fuel cells require a methanol/water fuel. Premixing of the fuel is commonly done for convenience and to control the possibility of contamination. Minimum maintenance will require periodic replacement of the fuel and air filters. Maintenance and service training specific to the fuel cell power plant may be required, even though the power plant will have a single manual start switch to initiate the internal computer-controlled startup sequence.



## 2.7 RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM)

The design Mean Time Between Failure (MTBF) of current 1.5-kW fuel cells is approximately 1500 hours. This estimate is based on component reliability estimates shown in Table 4 [3].

**TABLE 4**  
**FUEL CELL COMPONENT MTBF**

	<u>Hours</u>
• Cell Stack	250,000
• Reformer	55,000
• Pumps, Blower and Controls	2,630
• Power Conditioner	6,670

The reliability data for pumps and controls are consistent with standard military reliability projections. The estimate for a cell stack is based on laboratory tests of individual cell stacks in carefully controlled laboratory environments. Of singular concern is the potential for deterioration from contaminants which could be experienced in field use.

Exposure to sulfur or chloride contaminants introduced into the mixed fuel during preparation or storage will rapidly deactivate the fuel processor catalyst. The contaminated catalyst will not generate sufficient hydrogen to operate the cell stack. Continued operation with contaminated fuel will cause serious degradation of the cell stack.

## 2.8 ACOUSTIC NOISE AND INFRARED (IR) EMISSION

Acoustic noise from a fuel cell will be principally the result of fan noise. An acoustic test of the 1.5-kW unit was performed by UTC using the actual fan and a simulated housing. The results are shown in Table 5 for measurements at 6 meters and extrapolated to 100 meters. Based on these data and estimates of the increase in fan output at the higher levels of power production, our estimate of noise levels for a 10 kW unit fuel cell of this design are given in Table 5.

The infrared emission signature of the generator is related to the exhausted heat in the form of hot air, carbon dioxide and water vapor. Table 6 summarizes the expected exhaust of 0.5-kW and 10-kW units.

**TABLE 5**  
**ACOUSTIC NOISE OF A FUEL CELL GENERATOR**

<u>Frequency of Sound (Hz)</u>	<u>1.5-kW Unit</u>		<u>10-kW Unit</u>
	<u>Measured Sound Level at 6 Meters (dB)</u>	<u>Estimated Level at 100 Meters (dB)</u>	<u>Estimated Level at 100 Meters (dB)</u>
63	40	16	24
123	45	20	28

**TABLE 6**  
**WASTE HEAT EXHAUST OF A FUEL CELL GENERATOR**

<u>Generator Size (kW)</u>	<u>Waste Heat (Btu/Hr)</u>	<u>Average Temperature (°C)</u>
0.5	7,100	100-150
10	142,100	100-150

## 2.9 COST

For total power plants of significant size ( $>10$  kW), the cost is estimated to be ~\$2500/kW. It has been suggested that the 1.5-kW unit being developed for military use will cost \$3500/unit when delivered in large quantities of 50,000 per year.

## 2.10 PRODUCTION/TECHNOLOGY BASE

A production base for fuel cell technology consists of technical skill in the fabrication of components, stack assembly, fuel processor capabilities, system design and integration, and power plant construction. Companies having this overall capability include United Technologies Corporation (UTC), Westinghouse Electric Corporation with Energy Research Corporation, and Engelhard Industries.

A key to the required level of quality control and reliability is automated fabrication of cell components followed by assembly of cell stacks. UTC has by far the greatest current experience in terms of numbers and sizes of units produced.

The technology base has been built up over more than 20 years with expenditures, including the space program, running to several hundreds of millions of dollars. From these efforts viable technology has evolved on both phosphoric acid and alkaline cells. Molten carbonate fuel cell technology is emerging, but is not truly suited to mobile applications.

A reasonable understanding of the fundamentals of fuel cell technology has been established, and work is continuing in those areas where further progress may be anticipated. Some two dozen or more research teams are continuing work mainly in improving the catalytic activity of the electrodes and exploring the prospects for better electrolytes — the super acids. The objective in the catalysis work is improved performance with reduced precious metal loading, longer life, and tolerance to carbon monoxide and other catalyst contaminants.

### 3.0 TECHNOLOGICAL POTENTIAL OF THERMOELECTRIC GENERATORS

An identification of potential improvements in TEGs and fuel cells is desired to provide a picture of the future potential of these technologies to satisfy criteria related to the Army's tactical operations. The focus of this analysis is on basic technological developments as opposed to engineering design. In this context, the analysis moves out of the realm of existing technology and engineering design into considerations of fundamental, physical capabilities and limitations of the two technologies.

There is no unclassified evidence of air-cooled fossil-fueled thermoelectric generators built above 2 to 3 kW. Extension of the existing technology to 5-kW and 10-kW levels will be a substantial engineering challenge. We find no evidence of a fundamental technological barrier that will prevent development of a larger kW TEG. Throughout the following chapters we refer to the performance of the 5-kW and 10-kW units as a means of establishing characteristics of the 2.5- to 10-kW TEG family. This is not to suggest that the 5-kW and 10-kW units will be the forerunners of the family, for the near term Army development focus is on units less than 5-kW.

#### 3.1 TECHNOLOGY DESCRIPTION

A TEG is made up of three primary elements:

- the thermoelectric converter consisting of the thermopile, its housing and cooling system;
- the fuel management and delivery system; and
- the power conditioner.

A comprehensive description and analysis of current TEG technology is given in a report submitted to MERADCOM entitled "Engineering Assessment of TEG and TEG/FC Technology Growth Potential, Final Report, Phase I," dated September 1981. A discussion of the principles of operation and present design practice is presented in the Phase I report. For this analysis of the future potential of TEGs, it is important to understand that the efficiency of the TEG is governed by the average  $Z \cdot T$  product and by the temperature of the heated and cooled surfaces of the thermocouple.

where:

$T$  = Temperature at which  $Z$  is evaluated

$$Z = \frac{\alpha^2}{RK}$$

and

$\alpha$  = Seebeck coefficient of the TEG material

$R$  = Thermocouple electrical resistance

$K$  = Thermocouple thermal conductance

Present Lead Telluride converters have an upper hot end temperature limit of approximately 850-900°C (1500-1590°F) and are typically operated at approximately 600°C (1100°F). They have a maximum ZT value of approximately 0.5 and must be operated in an inert gas environment to prevent rapid deterioration of the thermocouple units. For a detailed discussion of this technology the reader is referred to the Phase I report [4].

Numerous other thermoelectric materials have been developed and studied [5]. Principle among the newer materials considered for further development are: Silicon Germanium, Selenides, Rare Earth (Lanthanum) Sulfides, and Boron Carbon.

Representative of materials likely to be introduced in the next 10 years is an improved Silicon Germanium doped with Gallium Phosphide. This material has demonstrated [6] a ZT of 1.3 at 1000°C and is projected to yield a converter efficiency (electric output/heat input) of 12.5% at 1000°C.

Work at Jet Propulsion Laboratories [7] and SynCal Corporation [8] have demonstrated values of ZT as high as 5.0 at 1250°C for Lanthanum Sulfide couples. However, the average ZT over the operating temperature range is not as high as that for Silicon Germanium material. Development work is underway to raise the ZT coefficient at the lower temperature (around 150°C). A temperature weighted average ZT of 2.5 (from 150°C to 1250°C) could result from these programs representing technological potential for the next 20 years. Under the conditions that the hot end temperature is 1000°C and a cold end is 150°C, the Lanthanum Sulfide could achieve a converter efficiency as high as 20%. Lanthanum Sulfide offers a high Seebeck coefficient and could produce 0.64 volts per thermocouple at these temperatures (as compared to 0.11 volts for present Lead Telluride generators) reducing the number of junctions required and increasing reliability. (See Section 3.6.)

Developments at Colorado School of Mines [9] indicate that new semiconductor materials such as Bismuth-Antimony can be produced in thin film ribbons; however, the demonstrated ZT is a mere 0.05. Further work is underway to reduce electrical resistivity and dramatically raise the ZT. Fabrication with ribbons could reduce the interconnection requirements, improving the expected meantime between failure for the thermoelectric converter.

Improved thermoelectric materials can improve the converter efficiency, and reduce costs, size and weight, but the maximum converter efficiency is governed by the relation: [9]

$$\text{electric efficiency} = \frac{\Delta T}{T_H} \frac{(1 + ZT)^{1/2} - 1}{(1 + ZT)^{1/2} + T_L/T_H}$$

where:

$T_H$  = hot end temperature

$T_L$  = cold end temperature

$\Delta T = T_H - T_L$

ZT = average ZT coefficient of the material over operative range where  
 $Z = \alpha^2 / RK$

$\alpha$  = Seebeck coefficient of the material

R = thermocouple electrical resistance

K = thermocouple thermal conductivity

Increasing values of ZT and  $T_H$  will increase the efficiency.

Achieving higher efficiencies and power densities (kW/lb) through new materials operating at higher hot end temperatures will involve additional engineering efforts in the heat exchange to the thermopile. A high-temperature regenerative heat exchanger, designed to recover combustion exhaust heat for preheating combustion air, will be necessary. A recovery efficiency up to 82% of the combustion energy could be achieved in the near term without condensation of the water vapor in the products of combustion. Higher recovery rates would probably require new combustion systems capable of condensing products of combustion.

One of the major difficulties in the design of a TEG is the adequate removal of heat from the cold junction. Ultimately, air is used as the cooling medium, though an intermediate coolant (liquid heat pipe) may be required to achieve compact modular design. Assuming that appropriate technology such as heat pipes, coolant loop, air manifold and management systems are developed, then the major technological gains for improving the cooling system lie in the area of the reduction of fan power requirements presently at about 14% of the gross output. This can be accomplished by improving the cooling system design by the use of larger face area (air flow area) air-cooled heat exchangers. Alternatively, energy could be recovered from the exhaust products to power the fans. A turbine/fan shared on a single shaft could be used to provide both the cooling air and the combustion air flows. If the minimum combustion gas temperature exiting the combustor is 560°C, there may be sufficient turbine shaft power to run both the cooling and combustion air blowers eliminating a substantial fraction of parasitic losses.

While the turbine/fan offers a reduction in fan power requirements, it has two drawbacks:

- It may reduce system reliability by adding a high-speed rotating turbine.
- It will require greater startup power because the combustion air must be pressurized.

Reducing air power requirements to 2-7% of the gross generator output through the use of low air velocity (large air flow area) air-cooled heat exchangers probably offers the best alternative for improved performance. This can probably be implemented with a liquid coolant circulated between the converter cold end and a fan-cooled large-air-flow-area heat exchanger.

### 3.1.1 Fuel Delivery and Management System

Improved fuel delivery systems could be developed that can enhance thermal performance. Opportunities exist for improved burner design that include catalytic burners (presently used by Teledyne in the 100- to 300-watt range) and advanced pulsed combustion systems designed to eliminate the need for forced air burners, thereby reducing substantially the parasitic losses.

Pulsed combustion burners have been implemented for natural gas units in residential and commercial boilers and furnaces. Figure 4 shows a cross-section of a unit which operates on the principle of controlled combustion in an aerodynamically designed chamber in which rapid ignition takes place approximately 60 times per second. This causes considerable pressure rise of the exhaust gases in the combustion chamber and forces the combustion products out of the combustion chamber and through the heat exchange section. The pressure rise in the combustion chamber is comparable to that produced by a fan but without the electric power requirement. (Alternatively, a turbine-fan unit operating off of the discharge gases of the combustor could be considered for reducing the parasitic electric requirements of the forced air unit, both for the combustion air and the cooling air requirements.)

The present pulsed combustion systems require a gaseous fuel which could be delivered by prevaporizing the fuel as shown in Figure 4. This would require substantial design innovation though it has the potential of eliminating combustion air fan power requirements amounting to 25 watts per kW.

Catalytic burners have been used in small-scale units by Teledyne and could be designed in a modular form to operate the larger TEGs. The advantages of catalytic operation are a stable flame and ease of reignition, typically within 30 seconds after blowout. Most catalytic burners operate at temperatures below 1000°C and are not presently suitable for use with the high ZT materials. The present Teledyne catalytic combustor offers little inherent improvement in thermal efficiency as this is governed by the heat exchange process in the generator and the ZT value of the thermopile. However, the catalytic burner is capable of operating with a wide variety of fuels, both gaseous and liquid.

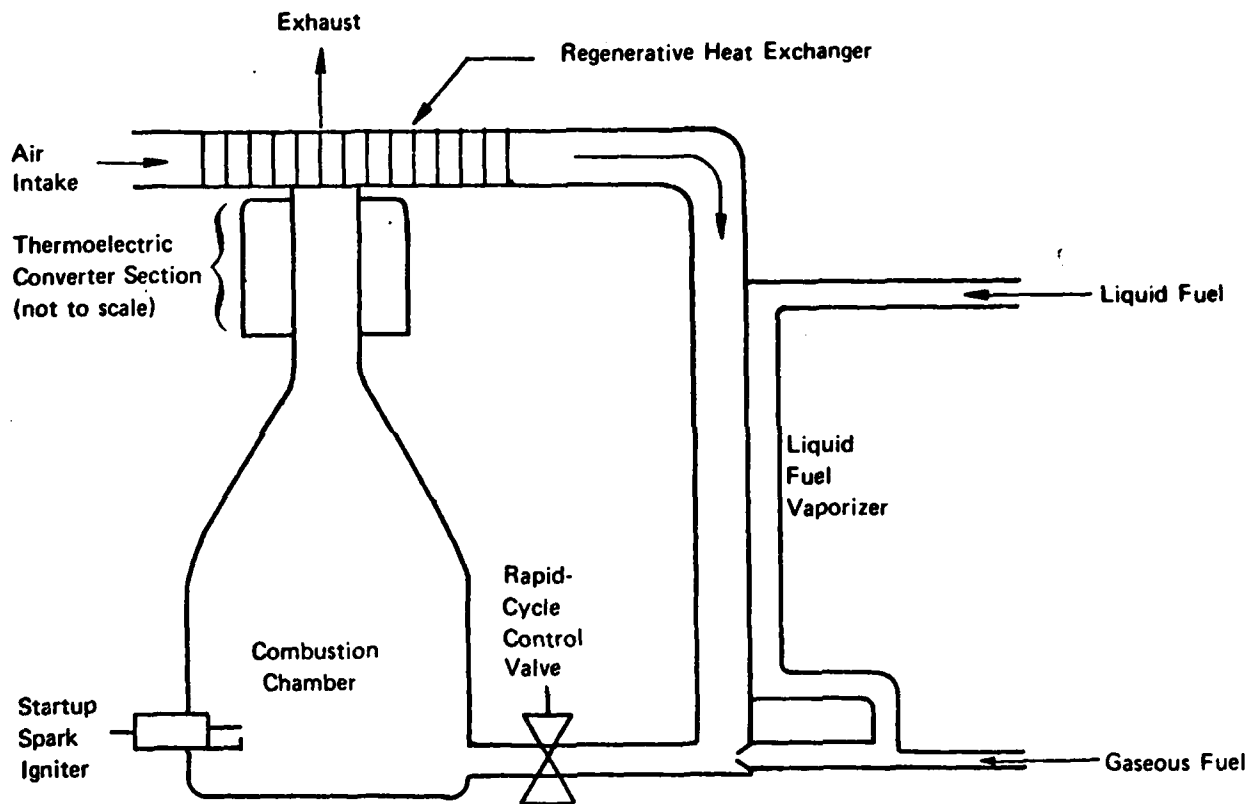


FIGURE 4 POSSIBLE PULSED COMBUSTION BURNER (GASEOUS FUEL OR LIQUID FUEL)



### 3.1.2 Auxiliary Power Drain

Present levels of electric power diverted to drive the cooling fan, controls, fuel pump and combustion fan amount to 22% of the gross output (140 watts out of 640 gross output). The auxiliary power requirements could be reduced to the levels shown in Table 7.

**TABLE 7**  
**AUXILIARY POWER REQUIREMENTS**

	<u>Auxiliary Demand as a % of Gross Output</u>
Cooling Fan (High Efficiency Heat Exchanger) <sup>a</sup>	2.4
Combustion Fan and Fuel Pump	2.5
Coolant Pump and Controls	<u>2.5</u>
<b>TOTAL</b>	<b>7.4</b>

<sup>a</sup>Designed to provide the required cooling with 2 CFM per net electric watt at 0.10 inch of watt pressure drop.

### 3.1.3 Power Conditioner

Improvements in the power conditioner can enhance net electrical efficiency as well as size and weight.

Present solid-state electronics could yield an 86% efficient power conditioner capable of meeting MIL Standard 1332B and delivering AC power with a weight penalty of 15 lb/kW plus 23 lb. Future developments in power conditioner technology are likely to raise the efficiency to 90% without added weight.

## 3.2 TECHNICAL PERFORMANCE AND EFFICIENCY

Materials such as Silicon Germanium or Rare Earth Sulfides, operating at higher temperatures can raise the specific power (kW per lb) and efficiency of the thermoelectric converter.

Improved Silicon Germanium doped with Gallium Phosphide capable of 12.5% gross efficiency [6] at 1000°C (hot end temperature) is representative of a potential technology in the next 10 years. High ZT materials [6, 8] such as Lanthanum Sulfide could reach gross efficiencies of 20% at 1000°C in fieldable units in 10 to 20 years, assuming advances are made in the ZT values in the low temperature regions.

The drop in power output with increased outdoor temperature will remain, and approximately a 7% loss in converter output can be expected with a rise in ambient temperature from 23°C to 51°C.

### 3.3 STARTUP PERFORMANCE

Startup performance of new TEGs could be improved as a result of the expected reduction in converter weight and thermal isolation of the cooling system (shut-down of liquid cooling pump) from the converter during startup. Assuming 10 lb/kW of converter thermocouple material must be heated to operating temperature, we have estimated the following startup times for TEG's in the 0.5- to 10-kW generator range. These estimates are presented in Table 8.

**TABLE 8**  
**STARTUP TIME**

<u>Converter Type</u>	<u>Time to Full Power</u>
Silicon Germanium	5-7 minutes
Rare Earth Sulfides	10-13 minutes

### 3.4 SIZE AND WEIGHT

The converter size and weight of future TEGs will be substantially less than current Army TEG converters. The improvements will come as a result of higher converter specific power levels (kW/lb) through the use of materials with higher ZT coefficients, and alleviating the need to operate the thermopile in an inert gas-filled container. Table 9 summarizes estimates of TEG weights and sizes.

While a linear increase in weight and size with generator power (Table 9) is not physically correct (typically the lb/kW would decline with increased generator power), it is sufficiently accurate in the limited power range of this study.

**TABLE 9**  
**SUMMARY OF PROJECTED TEG WEIGHTS AND SIZES**

	<u>Silicon Germanium</u>	<u>Rare Earth Sulfides</u>
Generator <sup>a</sup> Weight	40 lb/kW + 8 lb	36 lb/kW + 8 lb
Power Conditioner Weight	<u>15 lb/kW + 23 lb</u>	<u>15 lb/kW + 23 lb</u>
TOTAL	55 lb/kW + 31 lb	51 lb/kW + 31 lb
Generator Size	3 cu ft/kW	2.8 cu ft/kW
Power Conditioner Size	<u>0.4 cu ft/kW</u>	<u>0.4 cu ft/kW</u>
TOTAL	3.4 cu ft/kW	3.2 cu ft/kW

<sup>a</sup>Includes converter, burner, and cooling system for TEG.

The converter weight for the Silicon Germanium-based unit was estimated from data in the Jet Propulsion Laboratory study [7] and discussions with Valvo Raag of Syn Cal [6]. Jet Propulsion Laboratory estimated 23 lb/kW for a space application system including the thermopile, converter housing and the cold end radiator. Raag estimated 4.4 lb/kW for the thermopile. The converter weight including housing and support, wiring will probably be closer to 10 lb/kW. A regenerator of high temperature steel alloy for preheating inlet combustion air is estimated to weigh 13.5 lb/kW (assuming 172,000 Btu/hr of heat transfer for a 5-kW unit). A liquid-based cooling system was assumed in which coolant is circulated between the cold end of thermopile and an air cooled heat exchanger. An estimated 2.5 square feet of face area heat exchanger (all aluminum) weighing 46 lb. (for a 5-kW unit) would require 120 watts of fan power and would meet the cooling needs. An additional 6 lb/kW is attributed to burner, controls and frame. The battery weight (8 lb) is assumed to be relatively independent of generator size. (See Section 3.9 of Phase I Report.) A summary of the estimated component weights is given in Table 10.

While the power density of the Rare Earth Sulfides will be higher than that of the Silicon Germanium, no converter design analysis is available to determine the reduction. We anticipate that the converter weight and size of the Silicon Germanium unit is a fair representation of the Rare Earth Sulfides unit. A small reduction in the cooling system weight and size can be expected because of the higher electric efficiency.

**TABLE 10**  
**TEG COMPONENT WEIGHT ESTIMATES**  
(Based on a 5-kW Silicon Germanium Projection)

	Weight	
	lb	lb/kW
Thermopile Stack	50	10.0
Regenerator	67	13.5
Cooling System	46	9.2
Burner	15	3.0
Controls	5	1.0
Frame	15	3.0
Battery	8	NA
	<u>206</u>	<u>40 + 8</u>

### 3.5 LOGISTIC SUPPORT REQUIRED

The principle logistical support requirement will be standard fuels and personnel training. Personnel training for operation and maintenance will be required as the principles of operation are totally different from those of present field generators. The present TEG has demonstrated adequate performance with standard fuels such as gasoline. Performance with diesel fuel requires improvement for extended field application in kW size units. Table 11 summarizes the estimated fuel requirements.

**TABLE 11**  
**FUEL REQUIREMENTS**

<u>Thermoelectric Material</u>	<u>Fuel (lb/hr/kW)</u>
Silicon Germanium	2.0
Rare Earth Sulfides	1.0

### 3.6 RELIABILITY, AVAILABILITY AND MANTAINABILITY (RAM)

The reliability and operational availability of future TEGs will probably be determined more by the fuel supply, control, and electronics components than by the converter. Future converters will not be sealed in air-tight containers susceptible to pinhole leaks which could adversely affect performance. Additional thermopile reliability can be expected as a consequence of the higher thermocouple voltages of future materials (higher Seebeck coefficients and operation at higher temperature differentials) which will reduce the number of thermocouple junctions required to achieve the design voltage. The reduced

number of junctions can increase the converter reliability. A major technical problem to be solved for the high-temperature materials is fatigue and mechanical strain as a result of the temperature cycle stress on the materials.

The converter failure rate has been estimated at  $5 \times 10^{-9}$  failures per hour per element [10]. Silicon Germanium thermocouples produce 3.3 watts per couple, and hence 3030 couples (6060 elements) are required for a 10-kW generator. This amounts to an MTBF of 33,000. The estimated MTBF of other components and total system are shown in Table 12, and the estimated total MTBF for a 10-kW generator is shown in Table 13. The likelihood of a single 10-kW module is in doubt because of the extensive problems of construction, heat control and temperature stress on materials. If multiple smaller modules are needed to develop the 10-kW, the full load reliability will be reduced since the modes of failure will increase.

**TABLE 12**  
**COMPONENT MTBF FOR A 10-kW AC UNIT**

<u>Component</u>	<u>MTBF (Hours)</u>
Pump, Controls and Fan	3050 [11]
Power Conditioner	5000 [12]

**TABLE 13**  
**GENERATOR MTBF ESTIMATES FOR A 10-kW AC UNIT**

<u>System</u>	<u>Estimated MTBF (Hours)</u>
Silicon Germanium (303 couples/kW)	1800
Rare Earth Sulfides (119 couples/kW)	1805

MTBF for a DC unit is 2800 hours, and the upper limit for an AC system is 1900 hours even assuming an infinite MTBF for the converter and standard MTBF values for the components.

The generator availability will be very close to 99.6% assuming 4.0 hours for meantime to repair (MTTR) and 1.5 hours of scheduled maintenance every 1000 hours of operation.

Availability as used here is defined as:

$$A = 1 - \left( \frac{\text{MTTR}}{\text{MTBF}} + \frac{\text{maintenance time}}{\text{scheduled maintenance interval}} \right)$$

### 3.7 ACOUSTIC NOISE AND INFRARED (IR) EMISSION

Acoustic noise comes primarily from the cooling system fan. In general, the noise is a logarithmic function of the fan motor horsepower [13] which can be minimized with a large face area (low air velocity) heat exchanger. Table 14 summarizes the expected fan noise of a 10-kW generator, based on the measured noise of a 0.5-kW unit and assuming that a large face area heat exchanger results in an air side pressure drop of less than 0.3 inch of water.

**TABLE 14**  
**ESTIMATED 10-KW GENERATOR FAN NOISE**  
**WITH LARGE FACE AREA HEAT EXCHANGER**

<u>Hz</u>	<u>Measured Sound Level of 7.5-kW Unit at 5.4 Meters (dB)</u>	<u>Estimated Sound Level of 10-kW Unit at 100 Meters (dB)</u>	
		<u>Silicon Germanium Converter</u>	<u>Rare Earth Sulfides Converter</u>
63	63	37.6	32.1
123	66	38.6	36.1

These noise levels were estimated from a heat exchanger having the specifications shown in Table 15.

The infrared emission from the generator will be dominated by the exhaust from the cooling air amounting to 380,000 Btu/hr at 150°C for a 10-kW Silicon Germanium unit.

**TABLE 15**  
**SPECIFICATIONS OF COOLING HEAT EXCHANGER FOR NOISE**  
**ANALYSIS OF A 10-kW GENERATOR**

<u>Converter</u>	<u>Silicon Germanium</u>	<u>Rare Earth Sulfides</u>
Coolant Temperature	150°C	150°C
Air Temperature	52°C	52°C
Heat Rejection Rate	310,700 Btu/hr	167,000 Btu/hr
Weight/kW	9 lb/kW	5 lb/kW
Size/kW	0.6 cu ft/kW	0.4 cu ft/kW

### 3.8 COST

The cost of the generator can be broken down into the converter, power conditioner, fuel, and cooling system costs. Table 16 summarizes likely cost (in constant 1981 dollars) estimates for future generators assuming production volumes of about 50,000 units per year. Because of the complexity of establishing cost estimates, we have not attempted to substantiate the reported cost estimate of a Silicon Germanium converter. We estimate a unit cost of \$1350/kW for the Silicon Germanium system and \$1650/kW for the Rare Earth Sulfides system. The present industry-wide average cost of TEGs based on Lead Telluride and Bismuth Telluride is about \$28,000 to \$52,000/kW in production volumes of about 700 per year. These systems tend to be custom designs and include substantial one-time R&D costs. However, estimated future costs are nearly a 30-fold reduction from the present unit costs which puts the credibility of these projections in doubt.

**TABLE 16**  
**TEG ESTIMATED COST**

<u>10-Year Time Frame</u>	<u>Cost (\$/kW)</u>	<u>Source or Reference</u>
Silicon Germanium Converter	700	Reference 10
Power Conditioner	500	Arthur D. Little, Inc., estimate.
Auxiliary Plumbing, Controls, Fuel and Cooling System	150	Based on air conditioner, heat exchanger, and plumbing cost plus furnace burner and controls cost.
<b>TOTAL</b>	<b>1,350</b>	
<u>20-Year Time Frame</u>		
Rare Earth Sulfides Converter	1,000	Extrapolated from Silicon Germanium cost estimate.
Power Conditioner	500	Arthur D. Little, Inc., estimate.
Auxiliary Plumbing, Controls, Fuel and Cooling System	150	Based on air conditioner, heat exchanger, and plumbing cost plus furnace burner and controls cost.
<b>TOTAL</b>	<b>1,650</b>	

### 3.9 PRODUCTION/TECHNOLOGY BASE

The principle production base for TEGs in the United States is for remote power stations and space applications. A number of the current production, used mostly in space applications are operated with radioisotope heat sources which offer continuous power output for 1 to 10 years. Fossil-fueled TEGs are used for TV and telephone repeater stations, navigation lights, buoys and other remote applications. Table 17 shows the production base of TEGs, based on publicly available data. [10]

**TABLE 17**  
**PRODUCTION BASE OF TEGs**

Manufacturers	About 7 majors
Current Market Size	\$3.5 million of manufactured units per year
Average Product Volume	680 generators per year
Average Generator Output	100 watts DC output
Average Generator Price	\$5,200

The technology base of TEGs is somewhat greater than the manufacturing base. We estimate that three federal agencies (DOE, NASA, Army) are involved in TEG work and are supporting, to some extent, the seven major manufacturers and probably three to ten university programs. In addition, independent research is being done at the Jet Propulsion Laboratory and Energy Conversion Devices, Inc. on new TEG materials development.

Work, using different approaches, is presently underway to develop new thermoelectric materials (of high ZT values) at most of the firms or institutions mentioned above. A sample of the publicly known technological effort is listed below.

<u>Converter Type</u>	<u>Advanced Developer</u>
Silicon Germanium	JPL, SynCal
Copper Selinide	General Atomic, 3M
Amorphous Materials	Energy Conversion Devices, Inc.
Bismuth Antimony	DOE, Colorado School of Mines
Lanthanum Sulfide	JPL, SynCal
Boron Carbon	General Atomics

Undoubtedly, other proprietary materials developments are underway in the private sector.

There are few liquid fossil fuel field TEGs, and there is a limited technological base for new developments in this area. The primary work in this area has been done by Teledyne, 3M and Global Thermoelectrics.



## 4.0 TECHNOLOGICAL POTENTIAL OF FUEL CELLS

### 4.1 TECHNOLOGY DESCRIPTION

Future fuel cell technology for mobile applications will probably be based on acid electrolyte, despite better efficiency in alkaline systems. Removal of carbon dioxide from the air and fuel streams demands bulky equipment and a renewable carbon dioxide sorbent. Molten carbonate systems, operating at 600°C, will probably not be suited to mobile applications and intermittent use because of the fragility of the electrolyte tile and difficulties associated with thermal cycling.

Some improvement in stack performance will be achieved with improved catalysts and electrolytes, particularly on the air (cathode) side resulting in stack efficiencies close to 50%. It is also anticipated that the anode (fuel) catalyst will become more tolerant to impurities, particularly high concentrations of carbon monoxide and perhaps sulfur.

This latter prospect might be significant in achieving realistic multifuel capability; it appears that adiabatic reforming, a combination of partial oxidation and steam reforming, will permit the field generation of hydrogen from gasoline or diesel fuel. This is not practical at this time because of the impurity effects on the electrocatalysts. The overall efficiency of a power generator using an adiabatic reformer is less than that using low-temperature steam reforming because a larger proportion of the fuel is burned. Furthermore, if the anode exhaust is used as a source of water for the reformer, it is unavailable as a fuel to heat the reformer — another penalty in efficiency.

Recycling water from the anode exhaust to the fuel processor is a significant opportunity. Because water that is low in dissolved solids, particularly chloride ion, is needed to prevent contamination of the catalysts of the reformer and the cell stack, only purified water can be used. There would be a tradeoff between the loss of some of the thermal energy from combustion of the anode exhaust and the energy required to evaporate a liquid water feedstock. It may be argued that if water recycle is not possible and if purified water has to be supplied then methanol becomes the preferred fuel because of the higher overall efficiency of the methanol system.

The current 1.5-kW methanol-air fuel cell generator can be the precursor to higher efficiency units that will operate on a logistic fuel and not be dependent on a field supply of pure water.

## 4.2 3-kW, 5-kW AND 10-kW FUEL CELL SYSTEMS

To describe these different sizes of fuel cell generators as a family is perhaps misleading, even though they are generically similar. Each size presents unique problems in stack design, fuel processor design, conceptual design (multifuel, water recycling, etc.), and systems integration.

### 4.2.1 3-kW and 5-kW Technology

Recent engineering development programs at Energy Research Corporation (ERCO) have stressed component development, particularly the bipolar plate -- the intercell structure that is responsible for efficient gas distribution to the electrodes and for conductivity through the stack. Their studies have included conductivity, contact resistance, edge sealing and endurance in contact with phosphoric acid under the operating conditions of the cell stack. Up to 7000 hrs without visible deterioration was demonstrated.

In an electrode fabrication program, carbon-supported platinum and platinum-rhodium catalysts for 5" x 15" electrodes have been investigated [14]. The precious metal catalyst loading ranged from 0.2 to 1.0 g/ft<sup>2</sup>. Performance of electrodes based on graphite paper made hydrophobic with fluorinated ethylene propylene (FEP) was 100 A/ft<sup>2</sup> at 0.65 to 0.67 volts.

Similarly effective use of silicon carbide powder as the matrix to contain the phosphoric acid electrolyte was defined in an experimental program. The silicon carbide is put down as a slurry with polyethylene oxide and polytetrafluoroethylene (PTFE) in a coating process directly on to the electrodes [14].

Stack assembly was practiced with and without edge seals of Viton RTV<sup>®</sup> cement. When the seals were not used, the matrix was pre-wet with phosphoric acid. Viton was also used as gaskets in manifold seals. Satisfactory tests of thousands of hours were carried out with 80-cell stacks compressed at 72 psi (5400 lb).

### 4.2.2 10-kW Technology

The prospects for a 10-kW fuel cell generator are the most difficult to define; this size falls between the demonstrated 40-kW units and the smaller units. However, there is no reason to believe that this size presents intractable problems. Probably the prime issue is one of stack cooling since the fuel processor can be scaled advantageously (in terms of volume and weight), and the control problem is not significantly more difficult.

## 4.3 FUEL CELL MODULE TECHNOLOGY

### 4.3.1 Stack Cooling

One of the difficulties in discussing stack cooling is that the problems might be uniquely a function of stack output. For the smaller sizes, cooling with the cathode air supply is feasible – a recirculation loop gives a degree of control not possible with a single pass and reduces the inlet-outlet temperature differential. In larger stacks, perhaps starting at the 5-kW level, the air flow rate begins to create difficulties – large temperature differentials, poor air distribution and acid entrainment. Liquid cooling with an auxiliary heat exchanger gives good control, but corrosion problems, dielectric considerations, added complexity, and the reliability of a secondary system possibly offset the advantages.

The distributed gas (DIGAS) cooling passages used by ERCO seems to provide a solution – part of the air stream through the cell is diverted to cooling plates rather than the cathode (see Figure 2) so that the cathode air supply can be controlled separately and acid entrainment reduced significantly. (The air supply can, therefore, be recirculated for better control without risking excessive corrosion problems.) Stack cooling is essentially a systems problem that will need modelling and engineering testing. The problems are well within the bounds of present engineering capabilities.

### 4.3.2 Cell Stack

No fundamental changes are anticipated in cell stack configuration though there might be detailed design modifications to improve efficiency or reduce costs. Operating conditions for phosphoric acid stacks are probably already near the optimum, but if there is a change to the superacids (substituted trifluoromethane sulphonic acids) there will be significant differences in operating conditions. The temperature will be somewhat lower, 150°C. A temperature at which a carbon-monoxide-tolerant anode catalyst is needed. There is good promise of improved catalysts in current research. The details of heat and water removal will have to be defined but will not be very different from present practices. The superacids have the necessary chemical stability, better conductivity than phosphoric acid and also better solubility for oxygen and hydrogen. Higher solubility provides faster reactions at the electrodes.

Direct Oxidation (DO) of a fuel, other than hydrogen, would be a dramatic step forward. Cell stack configuration would not be different unless the concept involves packing a reforming catalyst in the anode space. Otherwise, the major change will be heavier catalyst loadings in the electrodes.

### 4.3.3 Fuel Processor

Providing multifuel capability to the fuel cell will require changes to the present fuel processor. One possibility is to utilize conventional steam reforming. However, this still would not provide the capability to handle diesel or No. 2 fuel oil. Adiabatic auto thermal reforming (ATR) offers a broader fuel flexibility.

The application of ATR to distillate fuel is still in the development stage although it has been used commercially for many years in ammonia plants (secondary reformer) and with natural gas-based methanol plants. Through screening studies sponsored by Electric Power Research Institute (EPRI), it was identified as an interesting technology for application to fuel cells to extend the fuel capability range of conventional steam reforming. Research has been underway at Jet Propulsion Laboratory (JPL), Engelhard Industries and United Technologies Corporation to investigate the optimum range for operating variables.

The ATR system differs from the current methanol and natural gas reformers in that the heat required for conversion is generated internally by combusting a portion of the fuel with air. This heat promotes the chemical reaction between the fuel and steam components. In addition, the operating temperatures are generally higher than for CSR, thereby offsetting the catalyst deactivation effect of sulfur. This permits the reforming of heavier hydrocarbons than does conventional steam reforming.

In the ATR process, superheated steam and air are preheated and fed to a vaporizing mixing chamber where fuel is injected. Partial combustion takes place in the entrance catalyst section, and the combustion products pass over the exit section catalyst for final conversion to hydrogen and carbon oxides. Incorporating an adiabatic reformer into a fuel cell processor would also require the addition of a carbon monoxide shift converter to reduce the carbon monoxide to levels acceptable to phosphoric acid fuel cells. Sulfur removal would also be necessary.

The initial step of vaporization of diesel and No. 2 fuel oil in conventional heat exchangers has been a problem experienced by the refining industry for many years. Heat exchangers in this service generally experience severe fouling and a reduction in their effectiveness. To avoid this problem, the UTC preheater design vaporizes the fuel by direct contact with superheated steam. Special attention has been paid to the mixing chamber in order to avoid fouling in that area.

The most critical aspect of the ATR processor is its tendency to produce carbon or soot at certain conditions. The formation of carbon represents an inefficiency and results in problems in the gas clean-up section. The primary variables affecting carbon formation include: oxygen fuel-carbon ratio, fuel quality, and to some extent, pre-reaction temperature. Of these, the sensitivity to oxygen/carbon ratio (type of fuel) is the most pronounced. No. 2 fuel oil and diesel are quite similar in their requirements for carbon-free operation, and gasoline is actually slightly easier to operate in the carbon-free region. This suggests that if the ATR processor was designed to handle No. 2 fuel oil, it should be capable of processing diesel and gasoline with minor adjustments to the fuel processing configuration.

The present methanol/water reformer weighs approximately 13 lb/kW of electrical output. The size and weight of the adiabatic reformer will probably decrease because the feed vaporizer and reactor are more compact than for an externally fired reformer. For example, there is no burner or separate combustion chamber for an ATR reactor. Offsetting this, however, will be the need for a zinc oxide sulfur removal canister and a carbon monoxide shift converter. Therefore, on balance, the weight of the overall fuel processor will probably increase in the order of 10-15%.

To date, UTC has tested ATR processors with capacities in the range of 2-20 kW equivalent. Therefore, scale to 3-kW, 5-kW and 10-kW units is not an issue. Indeed, scaling from 2-kW to 1.5-kW should be quite straightforward. Designing an ATR system for 500 watts is probably not practical. Instead, the system designed for 1.5-kW could be run at part load. This would obviously limit the turndown capability of the 0.5-kW unit.

#### 4.3.4 Direct Oxidation

In the 10- to 20-year time frames, Direct Oxidation (DO) may be operational. No fuel processor, as it is presently configured, would be necessary. Logistic fuels could be used in the cell stack directly, though the most likely candidate is methanol. Based on the limited data available, Direct Oxidation, while eliminating the need for an ATR, would reduce the cell stack voltage compared to the present value, so that the net efficiency would not change. Direct Oxidation would help to reduce weight and size.

#### 4.4 TECHNICAL PERFORMANCE AND EFFICIENCY

Present 6.4 Army fuel cell programs are focusing on methanol-water fuel cells with parallel development programs designed to develop multifuel capability. Important performance and logistic differences exist between the methanol and the multifuel fuel cell.

Table 18 summarizes the likely performance of future fuel cells in the 0.5- to 10-kW range.

**TABLE 18**  
**FUEL CELL GENERATOR EFFICIENCY**

	<u>Net A/C Electric Efficiency (%)</u>
10-Year	
Multifuel (ATR)	23
Methanol-water	30
20-Year	
Multifuel (DO)	28
Methanol (water recycle)	34

Future fuel cells like the present technology (see Section 2.3) will not be affected substantially by increased ambient temperature (to 52°C) and higher altitude operation.

#### 4.5 STARTUP PERFORMANCE

The startup performance of future fuel cells is not expected to differ much from the present technology (see Section 2.4) and a 10 minute startup is expected.

#### 4.6 SIZE AND WEIGHT

The size and weight of fuel cell systems in the next 10 years will be approximately the same size of the current units as shown in Table 19 and will be reduced in the 20-year time frame.

**TABLE 19**  
**FUEL CELL A/C GENERATOR SIZE AND WEIGHT**

	<u>Weight</u>	<u>Size</u> <u>(ft<sup>3</sup>/kW)</u>
<b>10-Year</b>		
Methanol	153 lb/kW + 23 lbs	5.5
Multifuel	180 lb/kW + 23 lbs	5.5
<b>20-Year</b>		
Methanol	66 lb/kW + 23 lbs	No estimate
Multifuel	96 lb/kW + 23 lbs	No estimate

The 10-year estimates reflect component weights of systems presently under development. Component weights for the 20-year systems are summarized in Table 20 and are based on data provided by ERC [15] and Arthur D. Little, Inc., estimates.

**TABLE 20**  
**ESTIMATED FUEL CELL WEIGHTS – 20-YEAR**  
**(SUPERACID STACK, WATER RECYCLE)**

<u>Methanol System</u>	<u>lb/kW</u>
Cell Stack (0.66V, 200 amp/ft <sup>2</sup> )	20
Reformer	10
Structure	5
Burner	3
Ducting and Plumbing	8
Controls	3
<b>SUBTOTAL</b>	<b>49</b>
Battery	1.6
Power Conditioner	15 lb/kW + 23 lb
<b>TOTAL</b>	<b>65.6 lb/kW + 23 lb</b>
 <u>Multifuel System</u>	
ATR Weight Penalty	30 lb/kW

#### 4.7 LOGISTIC SUPPORT REQUIRED

The use of an ATR fuel processor in the next ten years for a fuel cell unit would simplify the logistic support requirements, although purified water will be required. Since the ATR fuel processor may be capable of using gasoline, diesel and No. 2 fuel oil, the standard logistical fuel support system could be utilized. In fact, the unit should be capable of operating with JP-4 as well. In addition, the disposal of spent hydrogen sulfide removal canisters should pose no serious problem.

In the 20-year time frame, water recycle would eliminate the need for a specified water supply and allow the fuel cell to operate on current logistic fuels.

#### 4.8 RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM)

No substantial changes in reliability, availability and maintenance are expected over the present technology projection. (See Section 2.7.) A 1500 MTBF and 99.6% availability are projected for both time frames.

#### 4.9 ACOUSTIC NOISE AND INFRARED (IR) EMISSION

The acoustic noise and IR emission will be somewhat reduced in the future because of the increase in the electrical efficiency of the fuel cell that will reduce the fan requirement and quantity of exhaust gas. Table 21 summarizes our estimates.

**TABLE 21**  
**PROJECTED ACOUSTIC NOISE AND WASTE HEAT  
REJECTION OF FUEL CELLS**

	<u>Electric Efficiency (%)</u>	<u>Acoustic Noise</u>		<u>Waste Heat Rejection (Btu/hr)</u>
		<u>63 Hz (dB)</u>	<u>123 Hz (dB)</u>	
<b>10-Year</b>				
Methanol-Water	30	23.2	27.3	113,000
Multifuel	23	24.4	28.4	148,000
<b>20-Year</b>				
Multifuel/Water Recycle	28	23.5	27.5	122,000
Methanol/Water Recycle	34	22.7	26.7	100,000

#### 4.10 COST

Cost figures (Table 22) for the 10-year projection of potential technology were obtained in part from discussions with UTC and from analysis of power conditioner quotations. No substantial changes in the cost of the 10-year and 20-year projections are anticipated because of offsetting factors. While the additional years of manufacturing experience would reduce the cost of units produced from 1990-2000 incorporating direct oxidation and water recycle are likely to offset the reduction.

**TABLE 22**  
**FUEL CELL GENERATOR COST ESTIMATES**

	<u>10-Year Potential</u>		<u>20-Year Potential</u>	
	<u>Methanol</u>	<u>Multifuel</u>	<u>Methanol</u>	<u>Multifuel</u>
Cell Stack	\$ 700/kW	\$ 700/kW	\$ 700/kW	\$ 700/kW
Fuel Processor	300/kW	500/kW	300/kW	500/kW
Power Conditioner	500/kW	500/kW	500/kW	500/kW
Auxiliary Systems, Plumbing Controls of Fuel and Cooling System	700	700	500	650
<b>TOTAL</b>	<b>\$1500/kW+\$700</b>	<b>\$1700/kW+\$700</b>	<b>\$1500/kW+\$500</b>	<b>\$1700/kW+\$650</b>



## 5.0 COMPARATIVE ANALYSIS AND SUMMARY

### 5.1 COMPARISON OF TECHNOLOGICAL POTENTIAL

In the next ten years it is anticipated that TEGs will be developed with technologies represented by high performance Silicon Germanium thermocouples, operating at 1000°C at the hot end and 150°C at the cold end. Improvements in the liquid atomizer, burner and regenerative heat exchanger for a TEG will raise its reliability and thermal efficiency. Concurrent developments will result in composite catalysts tolerant to carbon monoxide and sulfur for phosphoric acid fuel cells.

The adiabatic thermal reformer (ATR) for fuel cells is expected to be operational within the next ten years, and multifuel capability for fuel cells will be realized, though a source of purified water will still be required.

We anticipate that engineering improvements in cooling system design will probably incorporate a liquid-based coolant system for larger TEGs in conjunction with standard forced air liquid-to-air heat exchangers. Fuel cell coolant systems are likely to remain air based, with the possible exception of the 10-kW unit. Fuel cell stack designs are intrinsically easier to cool by air than TEGs, because of the larger surface areas (lower heat flux). (Typical TEG heat flux rates are 0.9 watts/cm<sup>2</sup> for heat rejection from the thermocouple, while fuel cells are 0.3 watts/cm<sup>2</sup> from the cell stack plate.) Large cooling air fan losses can be used in the TEG through the use of large face area heat exchangers to minimize air pressure drop. Therefore, an intermediate means of heat transfer (liquid cooling) is probably the most simple means of removing heat from high-heat-flux thermocouples and transferring it to the low-heat-flux, large surface area, forced air heat exchangers. This can be accomplished with forced liquid coolants or heat pipes.

In the period 1990-2000, TEGs may operate with higher efficiencies as represented by Rare Earth Sulfides operating at 1000°C at the hot end. Advanced burners with high efficiency regenerative heat exchangers boosting heat recovery to above 90% could be available for liquid fuels. During this same period, fuel cells could benefit from the development of superacid cell stacks boosting the cell efficiency from 45% to 52% and water recycle which would reduce the need for a source of purified water. Advances in cell stack design could include the development of Direct Oxidation eliminating the need for a separate fuel processor.

## 5.2 TECHNICAL PERFORMANCE

### 5.2.1 10-Year Time Frame

The electrical efficiency of the generators is governed in part by technological limits of the cell stack or thermopile and by associated engineering constraints. This is due to thermal losses as well as parasitic electric requirements for fans, pumps and controls. The technological limitation on efficiency will be governed by fundamental materials development programs and basic physics. The engineering constraints on unit efficiency will be improved as a result of generator design and development work. The engineering subsystems having an identified effect on unit efficiency are the burner/fuel processor, power conditioner and auxiliary equipment requiring parasitic power.

As shown in Table 23, we anticipate that Silicon Germanium technology will demonstrate a thermopile efficiency of about 12%, while fuel cell stacks will run at approximately 45% in units that may be operationally tested within ten years. Through the use of regenerative heat exchangers in connection with the thermoelectric converter, TEGs could probably achieve an 83% burner efficiency (heat into thermopile per unit of fuel heating value). Fuels in the fuel cell are converted to hydrogen in the fuel processor and methanol-based fuel processors are likely to have thermal efficiencies of 90%, while multifuel processors are likely to demonstrate a 69% efficiency. Both fuel cells and TEGs will utilize similar power conditioners with electrical efficiencies of approximately 86%. Electric consumption to power fans, pumps and motors will probably reduce TEG output by 7%, and that of fuel cells by 14%. This difference is attributable to the potential for lower fan power requirements of TEGs through the use of remote large-face-area liquid-to-air cooling heat exchangers and to extra pumps and controls used in the fuel cell. A net thermal efficiency of 8.4% for TEGs and 30% for fuel cells is projected for the next ten years.

TABLE 23

## TECHNOLOGICAL POTENTIAL - 10 YEAR, TECHNICAL PERFORMANCE

1. Description	TEG	Fuel Cell
Converter/Stack	Silicon Germanium	Supported Pt catalyst phosphoric acid
Converter/Stack Temperature	1000°C hot end 150°C cold end	175°C to 200°C
Burner	Liquid atomizer	Liquid vaporizer
Cooling	Forced air/liquid coolant	Forced air
Power Conditioner	Solid-state	Solid-state
Fuel Processor	Not applicable	Low-temperature steam reforming; ATR
Parasitic Losses	Pump, controls, fan	Pump, controls, fan
2. Technical Performance <sup>a</sup>		
Technology		
Converter/Stack Efficiency	12.5%	Methanol 45% Multifuel 45%
Engineering		
Burner/Fuel Processor Efficiency	82%	69%
Power Conditioner Efficiency	86%	86%
Parasitic Multiplier	93%	86%
Net Efficiency	8.2%	23%

<sup>a</sup>All values are based on full power output.

### 5.2.2 20-Year Time Frame

TEG units will probably evolve to include Rare Earth Sulfides as the thermocouple material (or equivalent) and will operate at about 1000°C hot end temperature and 150°C at the cold end and achieve net electrical efficiencies of up to 16% (Table 24). Units would incorporate an efficient, condensing-type heat exchanger for preheating combustion gases as represented by pulse combustion technology. Some advancements in the cooling system technology can be expected, as would be represented by an advanced heat pipe system.

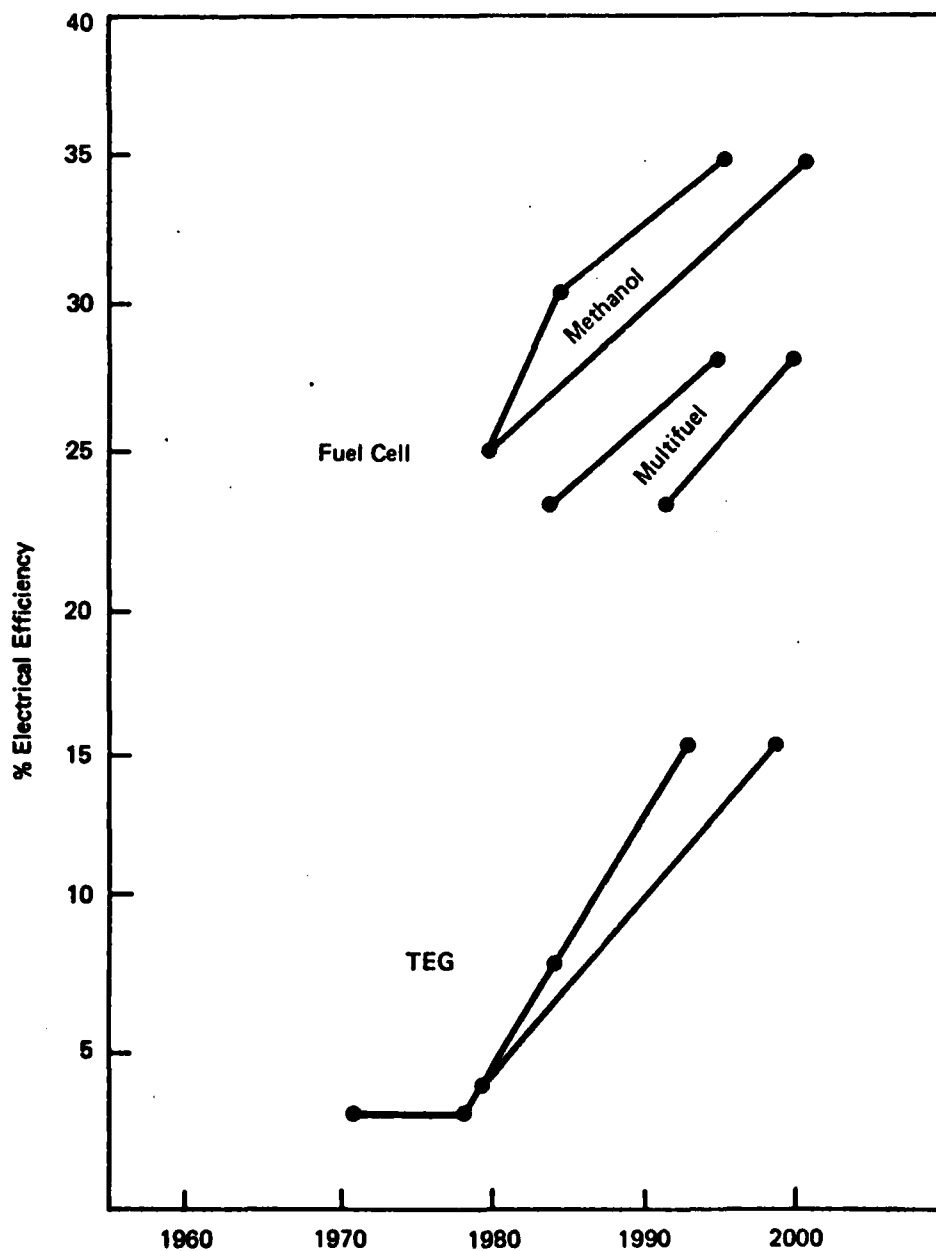
Fuel cell technology is likely to advance to incorporate superacid stacks with water recycled to eliminate the need for external purified water, and to incorporate Direct Oxidation for the multifuel systems. The multifuel systems will achieve efficiencies of 28% and the methanol-based units 34%. Figure 5 shows the present and projected electrical efficiency of TEGs and fuel cells. Two scenarios are depicted to indicate the uncertainty of the projections; one showing demonstration of the "technology" by 1990 and the other by the year 2000.

TABLE 24

## TECHNOLOGICAL POTENTIAL - 20 YEAR, TECHNICAL PERFORMANCE

1. Description	TEG	Fuel Cell	
		Multifuel	Methanol
Converter/Stack	Rare Earth Sulfides		
Converter/Stack Temperature	1000° hot end		
	150° C cold end		
Burner	Pulsed combustion		
Cooling	Advanced heat pipe		
Power Conditioner	Solid-state		
Fuel Processor	Not applicable		
			Super acids, water recycle 150° C
			Liquid atomizer
			DIGAS cooling
			Solid-state
			Direct oxidation-multifuel ATR-methanol
2. Technical Performance			
Technology			
Converter/Stack Efficiency	20.5%	52%	52%
Engineering			
Burner/Fuel Processor Efficiency	93%	69% <sup>a</sup>	81%
Power Conditioner Efficiency	90%	90%	90%
Parasitic Multiplier	95%	88%	88%
Net Efficiency	16%	28%	34%

<sup>a</sup>If direct oxidation is employed, this efficiency becomes 100%, but the stack efficiency is reduced by the same factor (0.69).



**FIGURE 5 SUMMARY OF GENERATOR ELECTRIC EFFICIENCY OF PAST AND PROJECTED UNITS FOR TACTICAL SERVICE**

### 5.3 STARTUP PERFORMANCE

A Silicon Germanium-based TEG could achieve rated output from a cold start in under eight minutes, while a comparably sized fuel cell will be at rated power in under ten minutes. The major difference in the startup characteristics is due to a TEG's large on-board main burner which is capable of quickly heating the converter stack as opposed to a considerably smaller auxiliary start burner used to heat up a fuel cell.

The startup time for Rare Earth Sulfides will be somewhat greater (under 15 minutes) since the units will weigh about the same as the Silicon Germanium converters, but will probably be heated by a burner that is nearly half the size. The fuel cell startup time for a superacid-based fuel cell will be reduced by 20% to about eight minutes because of the lower operating temperature of the superacid fuel cell.

### 5.4 SIZE AND WEIGHT

Table 25 summarizes the size and weight estimates for technologies which could be operationally tested in the next ten years. Silicon Germanium technology is projected to show a dramatic drop in size and weight over the present TEG systems lowering generator weight to about 40 lb/kW, including the burner and cooling systems. Fuel cell generator weights are expected to remain over 130 lb/kW for the methanol water fuel cells and a somewhat greater weight for the ATR multifuel units. Both fuel cells and TEGs will benefit from improvements in power conditioner technology where power conditioners weighing 15 lb/kW may be available. While there are differences in the power conditioners for fuel cells and TEGs, we do not expect these differences to show significantly in the size and weight.

In the 20-year time frame, the TEG converter size (Table 26) is expected to drop somewhat because of the high specific power of the Rare Earth Sulfides. Fuel cell weights will decline as the multifuel fuel cells will benefit from the incorporation of Direct Oxidation of fuels, nearly eliminating the fuel processor weight and improvements in the methanol stack design to include superacids which will improve the system weight slightly. In addition, higher cell stack current densities and more compact fuel processors are expected to contribute to weight reductions.

TEGs should require about an 8-lb battery for startup independent of generator size since the units can "bootstrap" up from a cold start. Fuel cell batteries will tend to scale with the generator size.

**TABLE 25**  
**TECHNOLOGICAL POTENTIAL – 10 YEAR, SIZE AND WEIGHT**

<u>Size and Weight</u>	<u>TEG</u>	<u>Fuel Cell</u>	
		<u>Methanol</u>	<u>Multifuel</u>
Generator Weight <sup>a</sup>	40 lb/kW + 8 lb	138 lb/kW	165 lb/kW
Power Conditioner Weight	<u>15 lb/kW + 23 lb</u>	<u>15 lb/kW + 23 lb</u>	<u>15 lb/kW + 23 lb</u>
<b>TOTAL WEIGHT</b>	55 lb/kW + 31 lb	153 lb/kW + 23 lb	180 lb/kW + 23
Generator Size	3 cu ft/kW	5.1 cu ft/kW	5.1 cu ft/kW
Power Conditioner Size	<u>0.4 cu ft/kW</u>	<u>0.4 cu ft/kW</u>	<u>0.4 cu ft/kW</u>
<b>TOTAL SIZE</b>	3.4 cu ft/kW	5.5 cu ft/kW	5.5 cu ft/kW

<sup>a</sup>Includes converter, burner, cooling for TEG/fuel processor, stack cooling, controls, base structure, battery.

**TABLE 26**  
**TECHNOLOGICAL POTENTIAL – 20 YEAR, SIZE AND WEIGHT**

<u>Size and Weight</u>	<u>TEG</u>	<u>Fuel Cell</u>	
		<u>Methanol</u>	<u>Multifuel</u>
Generator Weight <sup>a</sup>	36 lb/kW + 8 lb	50 lb/kW	80 lb/kW
Power Conditioner Weight	<u>15 lb/kW + 23 lb</u>	<u>15 lb/kW + 23 lb</u>	<u>15 lb/kW + 23 lb</u>
<b>TOTAL WEIGHT</b>	51 lb/kW + 31 lb	65 lb/kW + 23 lb	95 lb/kW + 23 lb
Generator Size	2.8 cu ft/kW	No estimate	No estimate
Power Conditioner Size	<u>0.4 cu ft/kW</u>	0.4 cu ft/kW	0.4 cu ft/kW
<b>TOTAL SIZE</b>	3.2 cu ft/kW		

<sup>a</sup>Includes converter, burner, cooling for TEG/fuel processor, stack cooling, controls, base structure, battery for the fuel cell.



## 5.5 LOGISTIC SUPPORT REQUIRED

In the next ten years, TEGs will be capable of operating with standard logistic fuels and will consume approximately 2 lb/hr/kW. The methanol-based fuel cell will require a specific methanol-water (purified water) mixture, while the multifuel fuel cell will operate on standard logistic fuels but will require a supply of purified water as shown in Table 27.

**TABLE 27**  
**TECHNOLOGICAL POTENTIAL – 10 YEAR, LOGISTIC, RAM AND COST**

<u>Logistic Support</u>	<u>TEG</u>	<u>Fuel Cell</u>	
	<u>Standard Fuels</u>	<u>Methanol/Water Premix</u>	<u>Multifuel</u>
Fuel (lb/hr)	2.0	Fuel and Water 2.0 Fuel Only 1.2	Fuel and Water 1.6 Fuel Only 0.8
<u>RAM</u>			
Reliability	1800 MTBF	1500 MTBF	
Availability	99.6%	99.6%	
Maintenance Ratio	0.004	0.004	
<u>Noise and IR (10-kW Unit)</u>			
Noise at 100 Meters	39 dB	27.3	28.4 dB
Waste Heat	380,000 Btu/hr at 140°-160°C	113,000 Btu/hr at 100°-150°C	148,000 Btu/hr
<u>Cost of 50,000 Units</u>			
Converter/Stack	\$ 700/kW	\$ 700/kW	\$ 700/kW
Fuel Processor	NA	\$ 300/kW	\$ 500/kW
Power Conditioner	\$ 500/kW	\$ 500/kW	\$ 500/kW
Auxiliary Plumbing, Controls, Fuel and Cooling System	\$ 150	\$ 700	\$ 700
<b>TOTAL</b>	<b>\$1,200/kW + \$150</b>	<b>\$1,500/kW + \$700</b>	<b>\$1,700/kW + \$700</b>

In the 10- to 20-year time frame, the TEG fuel requirement could be dramatically reduced to 1.0 lb/hr/kW (Table 28).

The fuel cell logistic requirements could be improved in the 10- to 20-year time frame through improvements in multifuel capability (DO) and through the development of water recycle.

TABLE 28

## TECHNOLOGICAL POTENTIAL – 20 YEARS, LOGISTIC, RAM AND COST

	<u>TEG</u>	<u>Fuel Cell</u>	
<u>Logistic Support</u>	<u>Logistic Fuels</u>	<u>Methanol</u>	<u>Multifuel</u>
Fuel (lb/hr/kW)	1.0	1.0	0.6
<u>RAM</u>			
Reliability	1800 (limited by electronics)	1500	1500
Availability	99.6%	99.6%	99.6%
Maintenance Ratio	0.004	0.004	0.004
<u>Noise and IR (10-kW)</u>			
Noise at 100 Meters 123 Hz	36.1 dB	26.7 dB	27.5 dB
Waste Heat	213,000 Btu/hr at 140°-160°C	100,000 Btu/hr	122,000 Btu/hr
<u>Cost of 10,000-100,000 Units</u>			
Converter/Stack	\$1,000/kW	\$ 700/kW	\$ 700/kW
Fuel Processor	NA	\$ 300/kW	\$ 500/kW
Power Conditioner	\$ 500/kW	\$ 500/kW	\$ 500/kW
Auxiliary, Plumbing, Controls of Fuel and Cooling System	\$ 150	\$ 500	\$ 650
TOTAL	\$1,500/kW + \$150	\$1,500/kW + \$500	\$1,700/kW + \$650

## 5.6 RELIABILITY, AVAILABILITY AND MAINTAINABILITY (RAM)

Both fuel cells and TEGs offer comparable levels of reliability, as shown in Table 27, and high percentage of availability. The RAM values will not change dramatically over the two time periods of interest. Table 27 summarizes the RAM values in the 10-year time frame, and Table 28 summarizes the 20-year values.

## 5.7 ACOUSTIC NOISE AND INFRARED (IR) EMISSION

A principal source of acoustic noise from these generators will be the cooling fan, and a fuel cell can be expected to run at rated power with less noise than a TEG. Since less heat must be dissipated from the fuel cell, lower fan noise could be expected. Tables 27 and 28 summarize the comparative values for the 10-year and 20-year frames, respectively.

## 5.8 COST

The potential costs of TEG and fuel cell technologies are also summarized in Tables 27 and 28.

## 5.9 PRODUCTION/TECHNOLOGY BASE

Table 29 summarizes the comparative production and technology base of fuel cells and TEG's.

**TABLE 29**  
**TECHNOLOGICAL POTENTIAL**

<u>Product/Technical Base</u>	<u>TEG</u>	<u>Fuel Cell</u>
No. of Manufacturers	About 7 majors	About 5 majors
Current Market Size	\$3.5 million	\$20 million
Average Production Volume	680 generators/year	500 generators/year
Average Generator Output	100 watts	40,000 watts
Maximum Power Commercial Unit	1000 watt (Global)	4,800,000 watts
Comment	Very few 1000 watts	Market trends to large size units
Anticipated Future Market for Terrestrial Applications	Limited growth	More commercial interest

## 5.10 TECHNOLOGICAL RISK

Table 30 summarizes the major technological risks associated with the two technologies for the future developments discussed in the foregoing chapters.

**TABLE 30**  
**TECHNOLOGICAL RISK**

<u>Risk (Technical and Cost)</u>	<u>TEG</u>	<u>Fuel Cell</u>
Scale Changes	Development risk	Little risk
Multifuel Capability	No risk	Development risk
Reliability	Both must be operationally tested in a tactical environment	
IR	Criteria must be set for acceptable IR	
Logistic Support	Training must be assessed for both technologies	
Part Load Performance	Development risk	No risk

We judge that scaling up the TEG to larger (0.5- to 5-kW) generator sizes will involve substantial development risk since basic questions of converter configuration remain. Scale up to the 10-kW size is most doubtful except as a combination of smaller units. Scaling of fuel cells from 1.5-kW up to 10-kW will involve little risk.

TEGs are presently multifuel generators, while fuel cells have not demonstrated an integrated multifuel capability. The present work on the ATR multifuel processor looks promising, but uncertainties exist concerning its being operational. For example, sensitivity to impurities in the fuel and the complexity of integrating the ATR into the generator.

Both TEGs and fuel cells should be operationally tested at the soonest date to determine reliability under field conditions. The Silicon Germanium and Rare Earth Sulfides TEGs and the fuel cells have unproven field reliability, and as such, we judge that reliability represents a development risk.

Until criteria for acceptable IR emissions are set, the compliance of either generator to IR specifications cannot be assessed. TEGs will exhaust larger amounts of heat than comparably sized fuel cells and represent more of a potential IR problem, but until the IR criteria are established, both technologies have a development risk in this area.

Both TEGs and fuel cells will require new training procedures for the Army user familiar with gasoline and diesel generators, and as such, training represents a development uncertainty.

## 5.11 SUMMARY

In summary, we find that both TEG and fuel cell technologies have growth potential. The trend may be to limit TEG to less than 5-kW sizes, and larger units may be multiples of the smaller modules. The fuel cells may be built in 3-kW to 10-kW modules, with smaller units operating at less than full power rating.

TEGs may have improved full load electric efficiencies through new materials development. The newer materials will afford a reduction in the size and weight as well. Reduction in the unit noise and IR emission can be expected in the future. TEG efficiency will fall off with part load operation.

Fuel cells may achieve multifuel capability with ATR and Direct Oxidation developments and realize improved efficiency with the superacids. Some reductions in weight and noise can be expected. The major growth area, however, is in development of multifuel capability. Fuel cells operate at normal efficiency down to 20 or 30% of rated load.

The growth in the commercial power plant technological base of fuel cells will probably be greater than that of TEGs because of higher efficiency and lower emissions of the fuel cells. However the industrial interest will not cover multifuel capabilities.

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